A Second Glitch from the "Anomalous" X-ray Pulsar 1RXS J170849.0−4000910

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ABSTRACT

We report on 5.4 yr of phase-coherent timing, using the *Rossi X-ray Timing Explorer,* of the X-ray pulsar 1RXS J170849.0−4000910 (1RXS 1708−4009), a member of the class known as "anomalous X-ray pulsars." This object exhibited a rotational glitch in 1999. Here we report a second much larger rotational glitch which occured ∼1.5 yr after the first. We show that the recoveries from the two glitches are significantly different, with the first showing only a possible slow, approximately linear recovery, while the second showed a nearly complete recovery on a time scale of ∼50 days. The approximately exponential recovery time scale of the second glitch is similar to that seen recently in 1E 2259+586 at the time of a major outburst. This suggests 1RXS 1708−4009 undergoes similar bursting behavior, although with our sparse observations we have detected no other evidence for bursts from this source.

Subject headings: pulsars: general — X-rays: general — pulsars: individual (1RXS 1708−4009)

1. Introduction

The exotic class of pulsars collectively known as "anomalous X-ray pulsars" (AXPs Mereghetti & Stella 1995; van Paradijs et al. 1995) has recently been shown (Gavriil et al. 2002; Kaspi et al. 2003) to exhibit short, hard-spectrum X-ray bursts that are very similar to those long seen in another equally exotic class of objects, the soft gamma repeaters

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(SGRs). The properties of the latter class have been well described by the magnetar model, in which the objects are isolated, young neutron stars that are powered by the decay of an enormous stellar magnetic field (Thompson & Duncan 1995; Thompson & Duncan 1996; Kouveliotou et al. 1998). In exhibiting bursts, AXPs have unified the two classes of object, and provided strong support that the magnetar model applies to both. However, what, if anything, physically distinguishes the two classes is still unknown. Observationally, AXPs appear to be the less active of the two source classes, with only one major bursting episode ever detected (and that, fortutously), compared with many seen from SGRs (see Hurley 2000, for a review).

1RXS J170849.0−4000910 (which, for brevity, we henceforth refer to as 1RXS 1708−4009) is an 11-s X-ray pulsar discovered by Sugizaki et al. (1997) in *ASCA* data, and shown to be spinning down like other AXPs by Israel et al. (1999). Kaspi et al. (1999) showed that the pulsar is capable of very stable rotation on the basis of $\sim$1.4 yr of *Rossi X-ray Timing Explorer* (*RXTE*) data that permitted phase-coherent timing using a simple spin-down model with only two free parameters. Kaspi et al. (2000) reported the discovery of the first rotation glitch seen in an AXP in data from 1RXS 1708−4009, and showed that the glitch had properties (e.g. fractional frequency change $\Delta\nu/\nu \simeq 6 \times 10^{-7}$) similar to those seen in the Vela radio pulsar and other radio pulsars like it (e.g. Shemar & Lyne 1996; Wang et al. 2000). The rotational stability away from the glitch and the similarity of the glitch properties with those seen in radio pulsars lent supporting evidence for the magnetar model. However, no activity beyond that single glitch has been reported for the pulsar.

Interestingly, the major bursting episode observed with *RXTE* from a different AXP, 1E 2259+586, was accompanied by a significant rotational glitch, having $\Delta\nu/\nu = 4\times10^{-6}$, of which a fraction $\sim$0.25 recovered on a time scale of $\sim$50 day (Kaspi et al. 2003; Woods et al. 2003). Also observed were short-lived pulse profile variations and an X-ray flux enhancement. This event occurred in spite of the pulsar having shown stable rotational behavior in over 5 yr of previous *RXTE* monitoring (Kaspi et al. 1999; Gavriil & Kaspi 2002), although the long-term past record hinted at episodes of activity (Iwasawa et al. 1992; Corbet et al. 1995; Baykal & Swank 1996; Heyl & Hernquist 1999). This behavior suggests that glitching may be a typical characteristic of AXPs during outbursts, and/or vice versa. However, with only one such event seen, such conclusions are tentative at best.

Here we report on continued *RXTE* monitoring of 1RXS 1708−4009. Our data set now extends over 5.4 yr. In this interval, in addition to the glitch reported by Kaspi et al. (2000), we have detected a second glitch $\sim$1.5 yr later. Accounting for both glitches in a phase-coherent timing solution that extends over the full data set, we find phase residuals of $<$2% of the pulse period. We compare the properties of the two glitches seen in 1RXS 1708−4009,

and show that their recoveries are quite different, with the second more closely resembling that seen in 1E 2259+586 in outburst. This suggests that 1RXS 1708−4009 may undergo similar bursting activity which has gone unseen by our sparse sampling.

Note that a subset of the data reported here has recently been analyzed as well by Dall'Osso et al. (2003), who reach similar though slightly different conclusions. We briefly discuss the differences between their results and ours.

2. Observations and Analysis

The *RXTE* observations described here are a continuation of those reported by Kaspi et al. (1999, 2000) and Gavriil & Kaspi (2002). We refer the reader to those papers for details of the analysis procedure. Briefly, all observations were obtained with the Proportional Counter Array (PCA Jahoda et al. 1996), with events selected in the energy range 2.5–5.4 keV to maximize the signal-to-noise ratio. The data we report on were obtained roughly monthly from 1998 January through 2003 May and were analyzed using software designed to handle raw spacecraft telemetry packet data. Data were binned at 31.25-ms time resolution and reduced to the solar system barycenter using the JPL DE200 ephemeris. Time series were folded at the nominal pulse period using 64 phase bins. Folded profiles were cross-correlated in the Fourier domain with a high signal-to-noise-ratio average profile in order to determine an average pulse arrival time. Resulting arrival times were analyzed using the `TEMPO` pulsar timing software package[5] in order to derive a fully phase-coherent timing ephemeris over the entire data set. Phase coherence over the glitches is accomplished under the assumption of zero phase jump at the time of the glitch – any non-zero phase jump would suggest an unphysically large torque on the star.

We assume a glitch model of the form observed for radio pulsars (e.g. Shemar & Lyne 1996),

$$\nu(t) = \nu_0(t) + \Delta\nu + \Delta\dot{\nu}t + \Delta\nu_d \mathrm{e}^{-t/t_d}, \tag{1}$$

where $\nu_0(t)$ is the pre-glitch spin ephemeris, $\Delta\nu$ and $\Delta\dot{\nu}$ are the permanent changes in ν and $\dot{\nu}$, and $\Delta\nu_d$ is the change in ν that recovers exponentially on a time scale t_d. Best-fit model parameters are given in Table 1. Figure 1 (top panel) shows the model long-term frequency history of the pulsar. The spin-ups, though small compared to the overall spin-down behavior, are just visible to the eye. Figure 1 (bottom panel) shows the same model with the linear trend removed, and the observed frequencies superimposed. These frequencies

[5]http://pulsar.princeton.edu/tempo

were determined using the same arrival time data, but by doing local fits for frequency using 3–4 arrival times per plotted point.

The first glitch (glitch 1) is modelled as a simple step in ν and $\dot{\nu}$ (Kaspi et al. 2000), i.e. has $\Delta\nu_d = 0$ in Equation 1. The second glitch (glitch 2), however, as can be seen from Table 1, has $\Delta\nu_d >> \Delta\nu$. A fraction $Q \equiv \Delta\nu_d/(\Delta\nu + \Delta\nu_d) = 0.96 \pm 0.11$ of the total frequency jump recovered following the glitch. This is consistent with a full recovery, and contrasts with glitch 1, for which $Q = 0$.

Furthermore, no significant change in $\dot{\nu}$ occured at glitch 2, unlike at glitch 1. We set a 3σ upper limit on a change in $\dot{\nu}$ relative to the long-term average of $< 2 \times 10^{-16}$ Hz s^{-1}. Dall'Osso et al. (2003) report a significant change in $\dot{\nu}$ at glitch 2, at first glance at odds with what we find. This is not because of their smaller data set post-glitch 2. We can reproduce their result when we fit for $\ddot{\nu}$ in the inter-glitch interval. Dall'Osso et al. (2003) are reporting an *instantaneous* change in $\dot{\nu}$ at the glitch epoch, while we report the change of the long-term averages. We believe the latter is more physically relevant, since the former can be contaminated (as is the case here) by noise. Indeed, that we find no change in $\dot{\nu}$ post-glitch 2 would have to be a coincidence otherwise. Reporting the instantaneous change in ν is appropriate however, because the evolution of ν is dominated by the deterministic spin-down.

Phase residuals following removal of the model given in the Table are shown in Figure 2. The RMS residual is $0.019P$, comparable to that seen for young radio pulsars (e.g. Arzoumanian et al. 1994). However, there are clearly unmodelled features in the residuals. The data pre-glitch 1 are well described by a simple model including only ν and $\dot{\nu}$. There is marginal evidence for $\ddot{\nu}$, but as discussed by Kaspi et al. (1999), its statistical significance is only 4σ, with removal of the very first data point giving 2.6σ. If real, this term could be due to timing noise or to recovery from a glitch that occurred prior to the commencement of the observations. The residuals between glitches, however, definitely show a significant $\ddot{\nu}$ as reported by Gavriil & Kaspi (2002). In that analysis, it was suggested that this could be recovery from a glitch. However, it could also be a manifestation of timing noise since the magnitude of the observed $\ddot{\nu}$ is comparable to that detected pre-glitch 1. The occurrence of glitch 2 precludes answering the question of the origin of the inter-glitch $\ddot{\nu}$. The residuals post-glitch 2, though overall described well by Equation 1, show small but significant deviations from that model. Initially, the recovery appears to be slightly slower than the exponential model, resulting in the relatively large residual just post-glitch. The longer-term post-glitch-2 residuals cannot be modelled well by any polynomial with fewer than 8 parameters. We can, however, model them reasonably well with only 4 parameters, if we ignore the glitch and consider only post-glitch data. That ephemeris is provided in Table 2, although we believe it is unlikely to have

precise long-term predictive power. We note that some young radio pulsars do not show simple exponential recoveries, but rather multiple recovery time scales (e.g. Lyne, Smith & Pritchard 1989).

Because of the bursting behavior seen in two other AXPs, we searched all PCA data obtained for 1RXS 1708−4009 for bursts. This was done by creating binned time series for each PCA proportional counter unit separately, using time resolution 31.25 ms. We used events in the energy range 2–20 keV. We used this wider energy range for the burst search compared to that used in the timing because of the observed relatively hard AXP burst spectra compared to the pulsed emission spectrum (Gavriil et al. 2002; Kaspi et al. 2003; Gavriil et al. 2003). A total of 310.5 ks of PCA exposure was searched, for the same time span as for the timing analysis. The burst search procedure used is described in detail by Gavriil et al. (2003). Briefly, large excursions from a local mean count rate existing in all PCUs were flagged using a Poissonian probability discriminator. No statistically significant bursts were found in any data for 1RXS 1708−4009. The upper limits on burst fluxes and fluences depend strongly on the (varying) local background rate, the burst morphology and the burst spectrum. Our sensitivity to bursts for 1RXS 1708−4009 is a factor of $\sim$3 below that for 1E 2259+586 (as estimated from the average total PCA count rates from both sources in the 2–20 keV band), and the faintest bursts detected for 1E 2259+586 have fluence $\sim 3 \times 10^{-11}$ erg cm^2 in the 2–10 keV band (Gavriil et al. 2003).

We also searched for pulsed flux and pulse morphology changes over the 5.4-yr time span, and especially just after the glitch epochs. Both were done with data in the 2–10 keV band and using the methods detailed by Gavriil & Kaspi (2002). The pulsed flux time series over the 5.4-yr span is similar in nature to that shown by Gavriil & Kaspi (2002), i.e. stable at the 20–30% level. Specifically, there is no evidence for enhanced pulsed flux post-glitch 2. Similarly, we find no evidence for large pulse profile changes at any epoch in our data set, including immediately post-glitch. However, our standard analysis procedure is not optimized for detection of low-level changes. We will present a more detailed pulse profile analysis elsewhere. We note that Dall'Osso et al. (2003) claim evidence for low-level pulse profile variations by comparing average profiles of data pre-glitch 1, between glitches, and post-glitch 2. However, those authors did not consider whether such low-level changes, occur in intervals that are not separated by glitches. Hence if real, the changes they found may be unrelated to the spin-up events.

3. Discussion

The two glitches observed in 1RXS 1708−4009 exhibit very different recoveries, as discussed in §2 above. Specifically, glitch 2 was dominated by a frequency jump that recovered exponentially on a ∼50 day time scale, while glitch 1 showed no such decay. Interestingly, the recovery seen in glitch 2 is very similar to that observed in 1E 2259+586 during its 2002 June outburst (Kaspi et al. 2003; Woods et al. 2003). For 1E 2259+586, however, $Q \simeq 0.25$ (Woods et al. 2003), different from the $Q \simeq 1$ seen for 1RXS 1708−4009. We note that although the first glitch was much smaller than the second, its long-term effect on the rotation of the pulsar is probably much greater, mainly because of its apparently permanent change in $\dot{\nu}$.

The similarity of glitch 2 for 1RXS 1708−4009 with that of 1E 2259+586 during outburst suggests that the former may have been accompanied by bursting behavior as well. Such bursts would have gone undetected because of the absence of any PCA observations near the glitch epoch. Indeed, the detection of the bursting from 1E 2259+586 was fortuitous, having lasted only a few hours. However, in the latter, the pulsed flux increased by over an order of magnitude at the time of the outburst and decayed on a time scale of weeks, remaining over a factor of two brighter for ∼3 weeks, but not returning back to its pre-burst value even after a year (Woods et al. 2003). The time between our best estimate of the glitch 2 epoch (Table 1) and the next observation of 1RXS 1708−4009 was 3 weeks, possibly long enough for a pulsed flux enhancement or major pulse profile change to have decayed beyond detectability. Hence the observations cannot rule out an unseen outburst at the time of the 1RXS 1708−4009 glitches.

It is interesting to compare the glitching properties of 1RXS 1708−4009 with those of the better studied radio pulsars. Glitches occur predominantly in radio pulsars having characteristic ages $\sim 10^3 - 10^5$ yr. Hence the glitches of 1RXS 1708−4009 support its youth, independent of its characteristic age. McKenna & Lyne (1990) introduced a glitch "activity parameter" for radio pulsars, defined as the sum of all frequency increments in a data span, divided by that data span duration. This quantity, admittedly on the basis of only two glitches in 1RXS 1708−4009, $\sim 3 \times 10^{-15}$ s^{-2}, is in the approximate middle of the distribution of glitch activities for radio pulsars (Wang et al. 2000), and two orders of magnitude smaller than that for observed for the Vela pulsar. The frequency of glitches in 1RXS 1708−4009, again, tentatively estimated from only two glitches, is ∼0.4 yr^{-1}, again in the approximate middle of the distribution for young radio pulsars, and substantially below the record holder, PSR J1341−6220 (Kaspi et al. 1992; Wang et al. 2000). The difference in recovery behavior between the two glitches seen in 1RXS 1708−4009 is not without precedent in radio pulsars; for example, both PSRs J1731−4744 and J1803−2137 have shown order

of magnitude differences in Q-values for different glitches (Wang et al. 2000). However, two 1RXS 1708−4009 glitch properties are unusual among radio pulsar glitches. The 50-day recovery time scale of glitch 2 is relatively short, although shorter recoveries have been seen for the Crab and Vela pulsars. In addition, the large Q of glitch 2 is unprecedented in radio pulsar glitches, the bulk of which are in the range 0–0.5.

In the context of vortex unpinning models (Anderson & Itoh 1975), glitches arise when vortex lines in the neutron-star crustal superfluid unpin from crustal lattice nuclei, then repin and transfer angular momentum from the faster rotating superfluid to the crust and coupled stellar core. Alpar et al. (1989) identified two regimes of glitch recovery: a linear regime in which a small superfluid-crust angular velocity lag suffices to unpin vortices because of weak pinning and for which the glitch decays exponentially, and a non-linear regime in which large lags are necessary and the glitch decays slowly or not at all. Alpar et al. (1989) suggested that hotter, hence younger neutron stars would exhibit predominantly linear-regime glitches, while colder, hence older neutron stars non-linear glitches. There is some evidence for this from studies of radio pulsar glitches (Wang et al. 2000; Lyne, Shemar & Graham Smith 2000). The detection of both types in 1RXS 1708−4009 indicates, in the context of this model, that both strong and weak vortex line pinnings are present in the crust. This is true of many radio pulsars. For a lengthier discussion of glitch models, see Dall'Osso et al. (2003).

If glitch 2 in 1RXS 1708−4009 was accompanied by unobserved bursts and persistent emission changes as observed for 1E 2259+586, the event could have resulted from a sudden event in the stellar crust, such as a crustal fracture, which simultaneously affected both the superfluid interior and the magnetosphere. Such a crustal fracture is an expected result of stresses due to the decay of the large stellar magnetic field. In this scenario, the fracture both triggered the vortex-line unpinning, and simultaneously shifted magnetic footpoints, resulting in a magnetospheric reconfiguration. Searches in future data from 1RXS 1708−4009 for behaviors like those seen for 1E 2259+586 during its 2002 June outburst are clearly warranted.

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Table 1. Spin Parameters for 1RXS 1708−4009.

Parameter	Value
Spin Frequency, ν (Hz)	0.0909136408(13)
Spin Frequency Derivative, $\dot{\nu}$ (Hz s^{-1})	$-1.5681(4) \times 10^{-13}$
Spin Period, P (s)	10.99944949(15)
Spin Period Derivative, $\dot{P}$	$18972(5) \times 10^{-15}$
Epoch (MJD)	51459.0000
Glitch 1	
$\Delta\nu$ (Hz)	$4.99(18) \times 10^{-8}$
$\Delta\dot{\nu}$ (Hz s^{-1})	$-0.0157(7) \times 10^{-13}$
Glitch 1 Epoch (MJD)	51444.601
Glitch 2	
$\Delta\nu$ (Hz)	$1.28(25) \times 10^{-8}$
$\Delta\dot{\nu}$ (Hz s^{-1})	$-0.0001(7) \times 10^{-13}$
$\Delta\nu_d$ (Hz)	$37(3) \times 10^{-8}$
t_d (days)	50(4)
Glitch 2 Epoch (MJD)	52014.177
RMS Timing Residual (ms)	213
Number of Arrival Times	81
Start Observing Epoch (MJD)	50826
End Observing Epoch (MJD)	52786

Note. — Numbers in parentheses represent 1σ uncertainties in the last digit quoted.

Table 2. Alternative Spin Ephemeris for 1RXS 1708−4009 Post Glitch 2.

Parameter	Value
ν (Hz)	0.0908958219(28)
$\dot{\nu}$ (Hz s^{-1})	$-1.540(7) \times 10^{-13}$
$\ddot{\nu}$ (Hz s^{-2})	$8.9(1.0) \times 10^{-22}$
$\dddot{\nu}$ (Hz s^{-3})	$8.6(8) \times 10^{-29}$
$\ddddot{\nu}$ (Hz s^{-4})	$3.46(26) \times 10^{-36}$
Epoch (MJD)	52766.000
RMS Timing Residual (ms)	184
Number of Arrival Times	39
Start Observing Epoch (MJD)	52035
End Observing Epoch (MJD)	52786

Note. — Numbers in parentheses represent 1σ uncertainties in the last digit quoted.

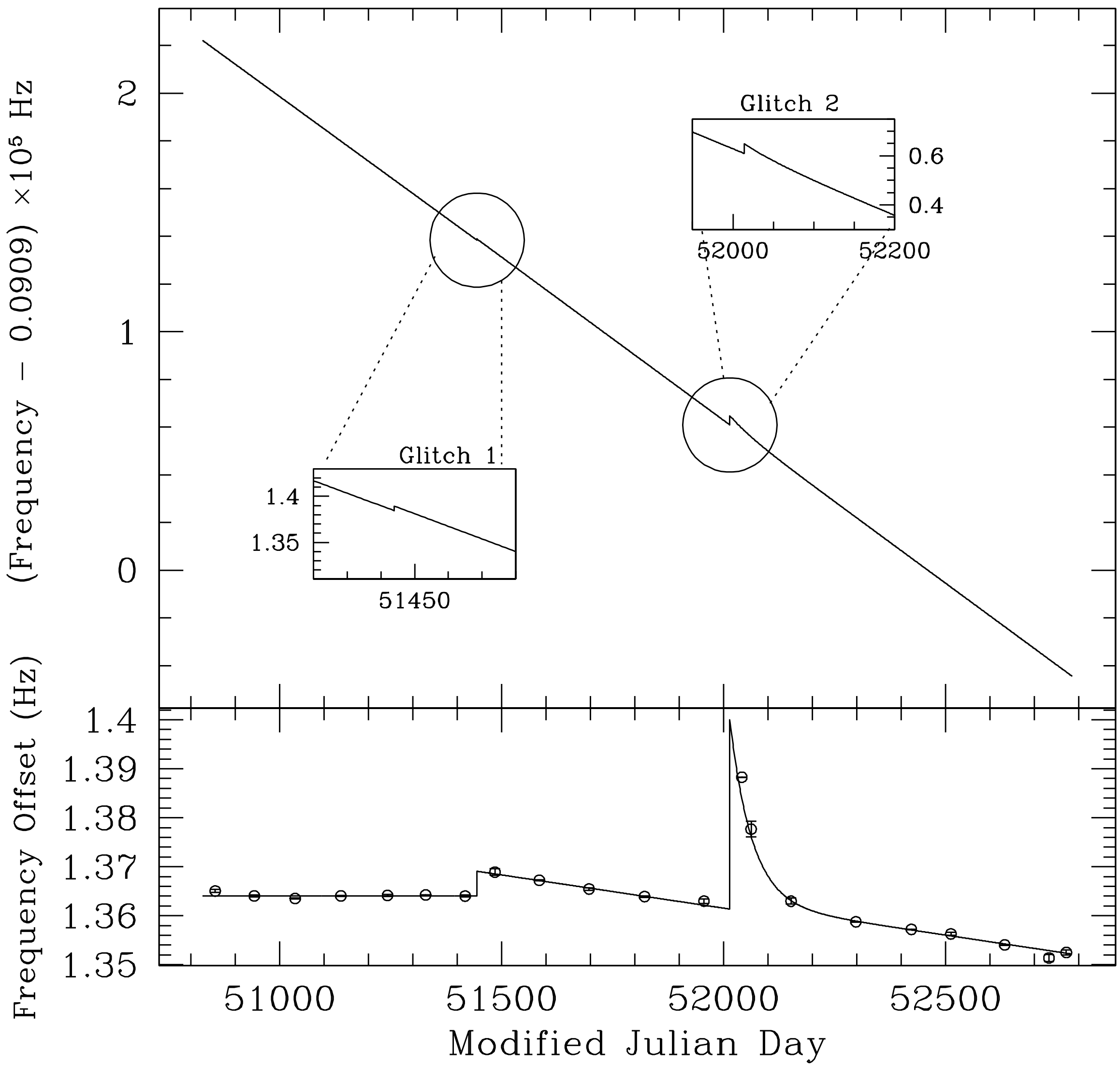

Fig. 1.— (Top) Model frequency history for 5.4 yr of *RXTE* monitoring (see Table 1). The glitches, superimposed on the overall spin down, are indicated by circles. The insets show the glitch data on an expanded scale. The recovery of glitch 2 is discernible by eye. (Bottom) The same model but with the linear trend removed, and frequencies referred to epoch MJD 51459.000. The two glitches are obvious. The data points, whose uncertainties are shown but which are generally smaller than the size of the point, were determined by doing local frequency fits using 3–4 arrival times per epoch.

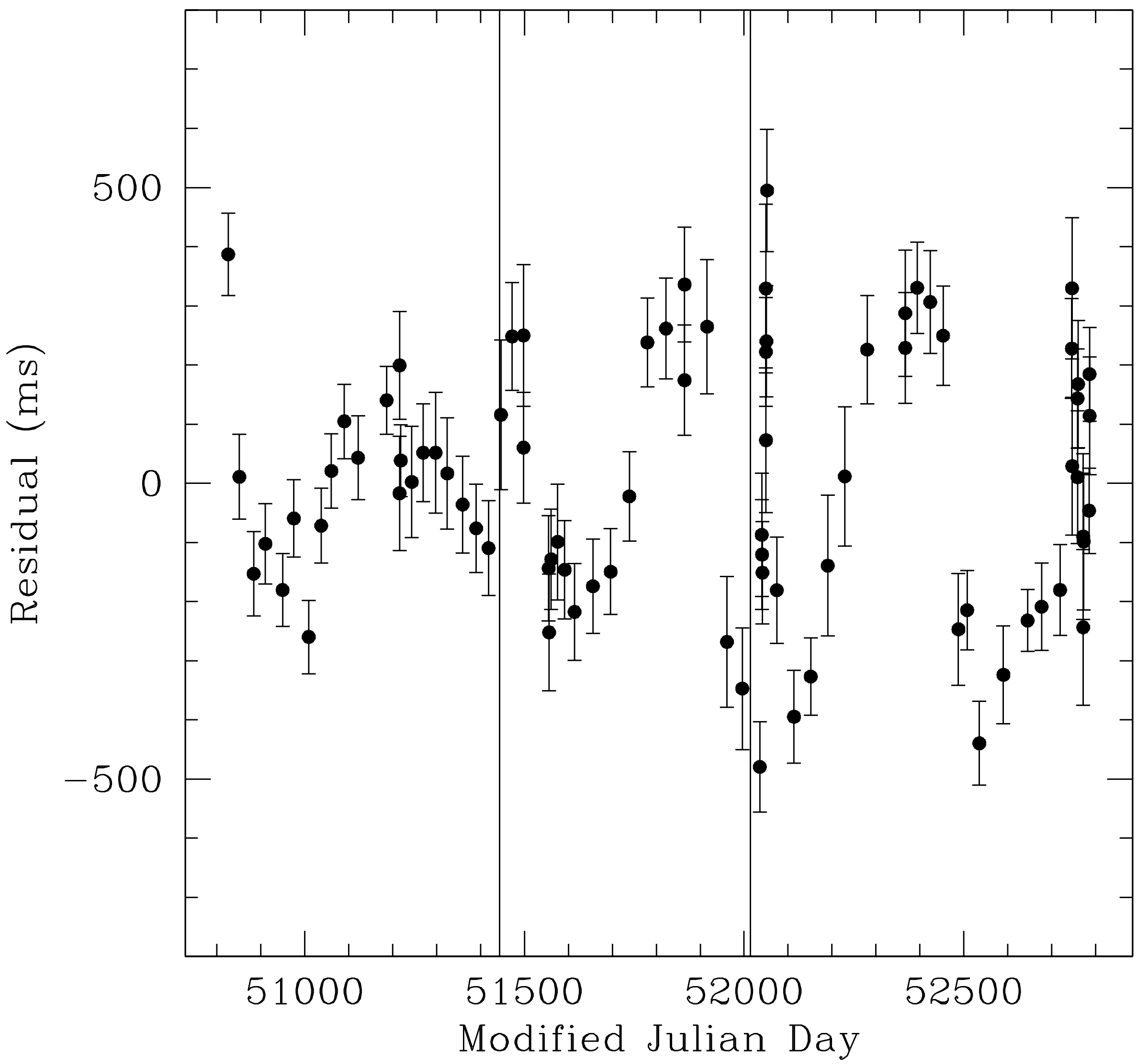

Fig. 2.— Phase residuals for 5.4 yr of phase-coherent timing of 1RXS 1708−4009, with the model shown in Table 1 removed. The best-fit glitch epochs are indicated with vertical lines. The RMS residual is 0.019 periods. Residuals pre-glitch 1 show marginal evidence for $\ddot{\nu}$ as discussed by Kaspi et al. (1999). Residuals between glitches show a significant $\ddot{\nu}$ which is consistent with standard recovery of the change in $\dot{\nu}$ as discussed in Gavriil & Kaspi (2002), but which may also be a manifestation of timing noise. Residuals post-glitch 2 show significant structure that indicates the short-time scale glitch response was slightly slower than exponential. The post-glitch 2 residuals can also be reasonably described by a polynomial fit with 4 parameters (see text and Table 2).